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14. ABSTRACT
This research is a comprehensive analytical and computational investigation of the dynamic response of planetary gears. In military helicopters, planetary gears are typically the last stage gear reduction whose output drives the main rotor. Their vibration is the dominant source of cabin noise. The project objectives are to:
- Develop analysis tools and engineering knowledge to reduce helicopter transmission dynamics and increase their reliability.
- Develop analytical, lumped-parameter models that capture the complex, nonlinear tooth mesh interactions typically

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Report Title

Final Report - Analytical/Computational Investigation of Planetary Gear Dynamics in Rotorcraft Transmissions

ABSTRACT

This research is a comprehensive analytical and computational investigation of the dynamic response of planetary gears. In military helicopters, planetary gears are typically the last stage gear reduction whose output drives the main rotor. Their vibration is the dominant source of cabin noise. The project objectives are to:

- Develop analysis tools and engineering knowledge to reduce helicopter transmission dynamics and increase their reliability.
- Develop analytical, lumped-parameter models that capture the complex, nonlinear tooth mesh interactions typically observed in multi-body, multi-mesh planetary gears.
- Validate analytical modeling with a unique finite element-contact mechanics formulation that captures the tooth mesh forces and contact mechanics with accuracy beyond that achievable with conventional finite element tools.
- Examine helicopter planetary gear dynamic response under operating conditions with coordinated analytical and computational simulations. Validate findings with experiments through related ARO DURIP and NRTC/RITA sponsored projects.
- Identify techniques to minimize planetary gear dynamics and the associated cabin noise with intelligent early design.
- Interact continuously with Army Research Lab staff at NASA Glenn and Army helicopter contractors regarding the Army technical needs and the findings of the research. Transfer technology and simulation tools to these parties and other US industry.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

R. G. Parker and J. Lin, Mesh Phasing Relationships in Planetary and Epicyclic Gears, ASME Journal of Mechanical Design, 2004, vol. 126, no. 2, pp. 365-370.

G.-J. Cheon and R. G. Parker, Influence of Manufacturing Errors on the Dynamic Characteristics of Planetary Gear Systems, KSME International Journal, 2004, vol. 18, no. 4, pp. 606-621.

G.-J. Cheon and R. G. Parker, Influence of Bearing Stiffness on the Static Properties of a Planetary Gear System with Manufacturing Errors, KSME International Journal, 2004, vol. 18, pp. 1978-1988.

S. Vangipuram Canchi and R. G. Parker, Parametric Instability of a Circular Ring Subjected to Moving Springs, Journal of Sound and Vibration, 2006, vol. 293, pp. 360-379.

V. K. Ambarisha and R. G. Parker, Suppression of Planet Mode Response in Planetary Gear Dynamics using Planet Mesh Phasing, ASME Journal of Vibration and Acoustics, 2006, vol. 128, pp. 133-142.

S. Vangipuram-Canchi and R. G. Parker, Parametric Instability of a Rotating Ring with Moving, Time-Varying Springs, ASME Journal of Vibration and Acoustics, 2006, vol. 128, pp. 231-243.

X. Wu and R. G. Parker, Vibration of Rings on a General Elastic Foundation, Journal of Sound and Vibration, 2006, vol. 295, pp. 194-213.

D. Kiracofe and R. G. Parker, Structured Vibration Modes of General Compound Planetary Gear Systems, ASME Journal of Vibration and Acoustics, 2007, vol. 129, pp. 1-16.

J. Lin and R. G. Parker, Planetary Gear Vibration Driven by Fluctuating Mesh Stiffness, Gear Solutions, 2007, vol. 49, pp. 32-45.

V. K. Ambarisha and R. G. Parker, Nonlinear Planetary Gear Dynamics using Analytical and Finite Element Models, Journal of Sound and Vibration, 2007, vol. 302, pp. 577-595.

S. Vangipuram-Canchi and R. G. Parker, Effects of Ring-Planet Mesh Phasing and Contact Ratio on the Parametric Instabilities of a Planetary Gear Ring, ASME Journal of Mechanical Design, 2008, vol. 130, p. 014501.

R. G. Parker, Natural Frequencies and Modal Properties of Compound Planetary Gears, Gear Solutions, 2008, vol. 6, pp. 26-35.

X. Wu and R. G. Parker, Modal Properties of Planetary Gears with an Elastic Continuum Ring Gear, ASME Journal of Applied Mechanics, 2008, vol. 75, p. 031014-1.

G. Liu and R. G. Parker, Nonlinear Dynamics of Idler Gearsets, Nonlinear Dynamics, 2008, vol. 53, pp. 345-367.

G. Liu and R. G. Parker, Dynamic Modeling and Analysis of Tooth Profile Modification for Multi-Mesh Gear Vibration, ASME Journal of Mechanical Design, 2008, in press.

G. Liu and R. G. Parker, Impact of Tooth Friction and Its Bending Effect on Gear Dynamics, Journal of Sound and Vibration, 2007, in press.

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Beijing University (China), Department of Engineering Science, Multi-mesh and Planetary Gear Dynamics, China, March 2004.

Tsinghua University (China), Department of Engineering Mechanics, Multi-mesh and Planetary Gear Dynamics, China, March 2004.

Risoe National Lab (Denmark), Dynamic Modeling, Analysis, and Experiments in Geared Systems, September 2004.

Rensselaer Polytechnic Institute, Department of Mechanical, Aerospace, and Nuclear Engineering, Nonlinear Dynamics of Multi-mesh and Planetary Gear Systems, October 2004.

University of Technology, Sydney (Australia), Faculty of Engineering, Multi-Mesh Gear Dynamics, February 2005.

University of New South Wales (Australia), Department of Mechanical and Manufacturing Engineering, Nonlinear Dynamics of Multi-mesh Gears, February 2005.

Australian Defence Science and Technology Organization, Multi-mesh and Planetary Gear Vibrations, February 2005.

University of British Columbia (Canada), Department of Mechanical Engineering, Nonlinear Vibration of Multi-mesh Gear Systems, March 2005.

Katholieke Universiteit Leuven (Belgium), Department of Mechanical Engineering, Dynamic Modeling and Analysis of Geared Transmissions, September 2005.

Hansen Transmissions (Belgium), Dynamic Modeling and Analysis of Geared Transmissions, September 2005.

LMS International (Belgium), Dynamic Modeling and Analysis of Geared Transmissions, September 2005.

Risoe National Lab (Denmark), Wind Energy Department, Wind Turbine Geartrain Dynamic Modeling, October 2005.

University of Bristol (UK), Department of Applied Mathematics, Nonlinear Dynamic Modeling and Analysis of Multi-Mesh Gear Systems, October 2005.

Italian Industrial Consortium, Gear Dynamics Modeling, Analysis, and Experiments in Industrial Applications, Modena Italy, November 2005.

National Technical University of Athens (Greece), Division of Mechanics, Nonlinear Dynamics of Multi-Mesh Gear Systems, March 2006.

Institut National des Sciences Appliquees - Lyon (France), Mechanical Engineering Department, Vibration Problems in Power Transmission Research, July 2006.

University of California, San Diego, Structural Engineering Department, Dynamics of Multibody Gear Systems, February 2007.

University of Southern California, Aerospace and Mechanical Engineering Department, Nonlinear Dynamics of Planetary and Multi-Mesh Gears, February 2007.

Orbital2 Corp., Analytical, Computational, and Experimental Dynamics of Industrial Gear Trains, March 2007.

Shanghai Jiaotong University, Analytical Insights and Computational Validation of Nonlinear Gear Dynamics, June 2007.

Plenary Speaker (expenses paid), Applied Nonlinear Mathematics Conference, University of Bristol (UK), Nonlinear Dynamics of Power Transmission Systems, September 2007.

Ohio State University, Department of Mechanical Engineering, Gear Dynamics: Practical Problems and Analytical Successes, October 2007.

Cornell University, Department of Theoretical and Applied Mechanics, Nonlinear Gear Vibrations: Practical Problems and Analytical Successes, January 2008.

University of New South Wales, Department of Mechanical and Manufacturing Engineering, Gear Dynamics, May 2008.

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

X. Wu and R. G. Parker, Modal Properties of Planetary Gears with an Elastic Continuum Ring Gear, Proc. of the 5th International Symposium on the Vibration of Continuous Systems, pp. 51-53, Berchtesgaden, Germany, July 2005, (conference participation by invitation only).

G. Liu and R. G. Parker, Nonlinear Dynamics of Idler Gear Systems, 5th EUROMECH Nonlinear Dynamics Conference, Eindhoven, Netherlands, August 2005, pp. 28-29.

T. Eritenel and R. G. Parker, Static and Dynamic Model for Three-Dimensional Multi-Mesh Gear Systems, ASME Power Transmission and Gearing Conference, Long Beach, CA, September 2005.

R. G. Parker, F. Rasmussen, and T. Larsen, Dynamic Modelling and Analysis of a Wind Turbine Planetary Gear with Tooth Backlash and Bearing Clearance, European Wind Energy Conference, Athens, Greece, February 2006.

X. Wu and R. G. Parker, Vibration of Rings on a General Elastic Foundation, 23rd Southeastern Conference on Theoretical and Applied Mechanics, Puerto Rico, May 2006.

C.-J. Bahk and R. G. Parker, Nonlinear Dynamics of Equally Spaced Planetary Gears, 11th Conf. on Nonlinear Vibrations, Stability, and Dynamics of Structures, Blacksburg, August 2006.

Y. Guo and R. G. Parker, Sensitivity of General Compound Planetary Gear Natural Frequencies and Vibration Modes to Model Parameters, ASME International Congress and Exposition, Chicago, November 2006.

S. Vangipuram Canchi and R. G. Parker, Parametric Instability of a Circular Ring Subjected to Moving Springs, ASME International Congress and Exposition, Chicago, November 2006.

S. Vangipuram Canchi and R. G. Parker, Vibration of Elastic Rings Parametrically-Excited by Moving Springs, International Congress on Sound and Vibration, Cairns, Australia, July 2007.

X. Wu and R. G. Parker, Resonant Vibration of Parametrically Excited Planetary Gears with an Elastic Continuum Ring Gear, 6th International Symposium on the Vibration of Continuous Systems, Squaw Valley, California, July 2007 (conference participation by invitation only).

S. Vangipuram Canchi and R. G. Parker, Parametric Instability of a Rotating, Ring with Moving, Time-Varying Springs, ASME 6th International Conference on Multibody Systems, Nonlinear Dynamics, and Control, Las Vegas, September 2007.

V. K. Ambarisha and R. G. Parker, Nonlinear Dynamics of Planetary Gears Using Analytical and Finite Element Models, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

D. R. Kiracofe and R. G. Parker, Structured Vibration Modes of General Compound Planetary Gear Systems, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

S. Vangipuram Canchi and R. G. Parker, Effect of Ring-Planet Mesh Phasing and Contact Ratio on the Vibration of a Planetary Gear Ring, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

C.-J. Bahk and R. G. Parker, Nonlinear Dynamics of Planetary Gears with Equal Planet Spacing, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

G. Liu and R. G. Parker, Tooth Friction and Its Bending Effect on Gear Dynamics, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

Y. Guo and R. G. Parker, Mesh Phase Relations in General Compound Planetary Gears, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

Y. Guo and R. G. Parker, Sensitivity of General Compound Planetary Gear Natural Frequencies and Vibration Modes to Model Parameters, ASME 10th International Power Transmission and Gearing Conference, Las Vegas, September 2007.

Y. Guo and R. G. Parker, Dynamic Modeling and Analysis of Planetary Gears Involving Tooth Wedging and Bearing Clearance Nonlinearity, 12th Conference on Nonlinear Vibrations, Dynamics, and Multibody Systems, Blacksburg, VA, June 2008.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 19

(d) Manuscripts

C.-J. Bahk and R. G. Parker, Nonlinear Dynamics of Planetary Gears with Equal Planet Spacing, ASME Journal of Computational and Nonlinear Dynamics, 2007, submitted.

X. Wu and R. G. Parker, Parametric Instability of Planetary Gears with Elastic Continuum Ring Gears, ASME Journal of Applied Mechanics, 2007, submitted.

S. Vangipuram-Canchi and R. G. Parker, Vibration of Elastic Rings Excited by Periodically Spaced Moving Springs, International Journal of Acoustics and Vibration, 2007, submitted.

Y. Guo and R. G. Parker, Sensitivity of General Compound Planetary Gear Natural Frequencies and Vibration Modes to Model Parameters, ASME Journal of Vibration and Acoustics, 2008, submitted.

Number of Manuscripts: 4.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Chris Cooley	1.00
Yichao Guo	1.00
Tristan Ericson	1.00
Cheon-Jae Bahk	1.00
Daniel Kiracofe	1.00
Xionghua Wu	1.00
Sanjib Chowdhury	1.00
Sripathi Vangipuram-Canchi	1.00
Tugan Eritenel	1.00
Gang Liu	1.00
FTE Equivalent:	**10.00**
Total Number:	**10**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert Parker	0.10	No
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME
Vijay Ambarisha
Sripathi Vangipuram-Canchi
Steve Martisauskas
Daniel Kiracofe
Andrew Del Donno
Chris Cooley

Total Number: 6

Names of personnel receiving PHDs

NAME
Gang Liu
Cheon-Jae Bahk

Total Number: 2

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Analytical/Computational Investigation of Planetary Gear Dynamics in Rotorcraft Transmissions

(Proposal No. 45578-EG)

Start Date: May 2004

Robert Parker
Department of Mechanical Engineering
Ohio State University, Columbus, OH 43210

I. Research Objectives

This research is a comprehensive analytical and computational investigation of the dynamic response of planetary gears (Figure 1a). In military helicopters, planetary gears are typically the last stage gear reduction whose output drives the main rotor. Their vibration is the dominant source of cabin noise, which can exceed 120 dB (Figure 1b). The project objectives are to:

- Develop analysis tools and engineering knowledge to reduce helicopter transmission dynamics and increase their reliability.
- Develop analytical, lumped-parameter models that capture the complex, nonlinear tooth mesh interactions typically observed in multi-body, multi-mesh planetary gears.
- Validate analytical modeling with a unique finite element-contact mechanics formulation for dynamic analysis of planetary gears.
- Examine helicopter planetary gear dynamic response under operating conditions with coordinated analytical and computational simulations. Validate findings with experiments, including through related ARO DURIP and Center for Rotorcraft Innovation/NRTC sponsored projects.
- Identify techniques to minimize planetary gear dynamics and the associated cabin noise with intelligent design early in the transmission selection process.
- Interact continuously with Army Research Lab staff at NASA Glenn and Army helicopter contractors regarding the Army technical needs and the findings of the research. Transfer technology and simulation tools to these parties and other US industry.

II. Approach

The most difficult aspect of gear dynamics is modeling the tooth contact. This study adopts two approaches (Figure 2): computational and analytical. The computational approach uses specialized finite element/contact mechanics/multibody dynamics software to capture the tooth mesh forces and contact mechanics with accuracy beyond that achievable with any conventional finite element methods. Sample results showing comparisons with experimental stresses in an Army OH58 helicopter planetary gear are shown in Figure 3 (experiments from ARL NASA Glenn) and comparisons with single mesh gear pair vibration in Figure 4. Planetary gear dynamic response analyses of the fidelity achievable with this model do not exist. No assumptions are made on the nature of the dynamic mesh forces; they are determined implicitly at each time step from a detailed contact analysis based on the current position of all gear bodies as they rotate. This contrasts sharply with conventional tools where the mesh forces, which are poorly known and subject to much modeling debate, are externally specified.

In a parallel effort, a lumped-parameter model that represents the gears as rigid bodies interconnected by springs modeling the tooth meshes is employed (Figure 2b). The intent is to

develop this simpler model in conjunction with the computational model to capture the critical dynamic phenomena. Modeling of this type would find regular use in engineering practice to predict natural frequencies and dynamic response early in the design phase. It is also a basic research tool for investigators to mathematically study and easily simulate the complex dynamics of planetary gears. Great advances have been made in recent years for comparable models of a single pair of gears, and that work illuminates the importance of nonlinear dynamics in practical gear use. This project will extend these advances to the more complex multi-body, multi-mesh planetary gears.

These models serve different purposes: The finite element model is for detailed study of particular phenomena and designs, and the lumped model is for research, early design, and building simple, non-proprietary simulation tools. Our purpose is to develop these models in parallel with findings of one guiding development of the other.

III. Significance

Measured helicopter cabin acoustics reveal planetary gear vibration as the dominant source of cabin noise. Figure 1b shows that all dominant peaks in the helicopter noise spectrum are at the planetary gear mesh frequency (number of teeth that pass through mesh per second) and integer multiples of this mesh frequency. Furthermore, the frequency of the noise is in the range most audible by humans. Planetary gear induced cabin noise, which can exceed 120 dB, results in operator fatigue, communication difficulty, discomfort, and health risks from extended exposure. Additionally, the dynamic loads reduce reliability and service life while the additional weight needed to sustain these loads reduces payload. Acoustic treatments alone weigh up to 500 *lb*. These concerns limit helicopter effectiveness in military and civilian applications.

In current Army contractor practice, planetary gear vibration is minimally considered and addressed by *ad hoc* design guidelines, many of which rely on empirical observations rather than engineering understanding and scientific models. This creates excellent opportunity for progress of practical significance. The modeling and analysis of critical dynamic behavior from this research will provide a firm foundation for helicopter transmission design and analysis that is currently lacking. A major activity with Sikorsky (see Technology Transfer below) illustrates the rotorcraft industry importance.

The finite element and lumped-parameter analysis tools developed in this research will be available for use by Army helicopter contractors. These tools are notably lacking in engineering practice despite the importance of planetary gears in helicopters, cars, heavy machinery, ground vehicles, and other applications. Planetary gears have received little prior research attention as most gear dynamics studies address the simpler case of a single pair of meshing gears. Thus, the potential for scientific advancement and near-term practical impact is excellent.

Considering non-defense applications of importance to US industry, the developed models have been applied to wind turbines, cars, and aircraft engines (see Technology Transfer below). In some cases, these industries have provided research funding that augments ARO's planetary gear dynamics investment in my lab.

Collaborative Relationships and Additional Sponsorship

The PI has collaborative relationships within the rotorcraft, automotive, aircraft engine, and wind turbine industries that fund additional research relevant to the ARO project objectives. This leverages ARO funds as much of the work conducted addresses modeling issues that cross industries. These efforts expand the core of graduate students cooperating in the lab, and there is considerable crossover in technical knowledge that works to the benefit of all (subject to proprietary information agreements), especially the rotorcraft industry.

The PI has ongoing sponsored research with the Center for Rotorcraft Innovation (CRI) to conduct experiments on planetary gears using the PI's ARO DURIP test stand. This funding was renewed in 2008 for three years. In March 2006, they used the OSU test stand for proof of concept testing of a novel planetary design. The hardware for use on OSU's stand cost in excess of $400k, indicating the value they place on having a test facility like that funded by ARO DURIP. Sikorsky has initiated a project with the PI on dynamic modeling of a new rotorcraft transmission.

General Motors has sponsored related research by the PI since 2000. Their interest is model development for multi-mesh systems for use in manual and automatic transmissions. Ford recently initiated research with the PI for analytical modeling of compound planetary gears, including support for experiments. The PI and Ford have cooperated closely on the design and manufacture of precision planetary gear experimental hardware. Honeywell Aircraft Engines started a project on modeling geared systems linked to continuous system elements such as shaft vibration or elastic ring gear vibration in planetary systems. A wind turbine company (Windflow) worked with the PI on planet mesh phasing in a practical system with exceptional results demonstrated on a practical system (see below). The PI has used his dynamic models in support of six other wind turbine gear dynamic analysis projects. He developed close ties to the wind turbine industry while conducting gear vibration research at Risoe National Lab in Denmark in 2005.

IV. Accomplishments in the current grant

- **Partnership with Penn State on US Army Vertical Lift Research Center of Excellence** I partnered with researchers at Penn State on a successful US Army Vertical Lift Research Center of Excellence proposal for five years of support. We are in the second year of that project. My project on transmission dynamics was rated highly in review and selected for ongoing support (while many other projects were omitted). This strengthens my links with the Army, rotorcraft industry, and other researchers in this area. I received excellent response from a high-level ARL/industry review team when presenting the research in April 2008.

- **Vibration Reduction Using Tooth Profile Modifications** – One of the most effective ways to reduce gear noise is to modify the tooth shape very slightly, typically a few μm (Figure 6). There is virtually *no additional expense* to use tooth modifications. This practice is used universally in industrial practice, where the methods are based on single mesh systems. No past study exists on how to apply this concept to planetary systems. A PhD student conducted a dual analytical/computational study to develop effective models for dynamic analysis of planetary gears with tooth modifications. This has exposed two key items: a) tooth modification can be extremely effective in planetary gears (see amplitude reduction in Figure 6), and b) analytical modeling requires attention to important details that have been ignored in the past; conventional models adapted from single mesh systems are not effective. The computational analysis has shown the ability of the finite element model discussed above to capture the nonlinear vibrations of gears and their sensitivity to tooth modifications.

- **Dynamic Analysis of Compound Planetary Gears** – Transmissions frequently use multiple planetary gears connected together (multi-stage). They also use compound planetary gears with multiple planets between sun and ring (Figure 7) or multiple planets on the planet shaft (Figure 7). Such systems increase the gear reduction ratio in a more compact space while retaining traditional advantages of planetary gears such as high

torque-weight ratios and division of load between multiple load paths. We completed a full mathematical model of compound planetary gears of very general description. This includes multiple stages, where each stage can have the meshed or stepped planet arrangement in Figure 7. In the last year, we completed a full mathematical characterization of the highly structured natural frequency and vibration mode properties of these systems. *All* modes fall into one of three types: rotational, translational, and planet modes. Knowledge of these basic properties is crucial for analysis of dynamic response, parametric resonance from changing mesh stiffness, and contact loss nonlinearity. We also completed a sensitivity study that shows how the vibration properties change with system parameters. These sensitivities are captured in simple analytical expressions. The developed compound planetary gear model is being used for a project with Sikorsky Aircraft.

- **Modeling of Planetary Gears with Elastic Ring Deflection** – The ring gear's large diameter (ranging from 12-30+ inches) and thin cross-section make it a flexible structure for the magnitude of loads that occur in helicopter operation (see exaggerated deflection shown in Figure 8a). In fact, some helicopter manufacturers deliberately design to promote elastic ring deflection as a way to equalize loading between planets. The stress contours and experimental data in Figure 3 confirm elastic ring vibration occurs as it is evident that large stress occurs at the ring gear teeth even when the strain gaged tooth is far from a tooth mesh of the rotating planets (which are indicated by the red color and the sharp spikes in the graphs). Elastic ring deflection has never been captured in prior planetary gear analysis, even though it has been observed and measured. This is due to the limited state-of-the-art of prior planetary gear analysis and the mathematical difficulty of incorporating a continuum structure (partial differential equation) into gear models that typically represent the gears as rigid bodies with only translational and rotational motion. A Ph.D. student developed a coupled continuum-discrete model that includes elastic ring gear deflection (Figure 8b). The ring is coupled to the other gears by the meshing teeth, which are represented as discrete stiffnesses. The full planetary gear model has been used to compute natural frequencies and vibration modes. The computed natural frequencies show that elastic ring vibration significantly affects the system dynamics compared to existing rigid ring models. Recently we completed a mathematical characterization of the structured vibration modes of this system.

- **Nonlinear Planetary Gear Dynamics** – Analysis of single gear pairs, idler gear systems, and supporting experiments demonstrate the importance of contact loss in gear vibration. Audible noise confirms this. Contact loss nonlinearity complicates the modeling and analysis. Numerical simulations of the analytical model and the finite element validation both exhibit strong nonlinearity. The agreement between the independent models confirms the physical assumptions of the analytical model. A PhD student developed a perturbation analysis that gives a great deal of insight into the nonlinear vibration in simple analytical expressions. The structured modal properties of planetary gears discovered with ARO support are valuable in this analytical solution. Certain modes are more susceptible than others to large amplitude response and contact loss. This is important to assess the vibration and noise potential of candidate planetary gear designs.

- **Bearing Clearance and Tooth "Wedging" in Planetary Gears** – Premature failure of the planet bearings is a concern in rotorcraft applications operating at high loads. One cause of this early failure may be elevated bearing forces caused by "wedging" of the

meshing gear teeth. This means simultaneous contact on both sides of one tooth. This behavior can occur from freeplay or clearance in the bearings. A PhD student developed a comprehensive nonlinear model that includes wedging and bearing clearance. Numerical simulations of this nonlinear model confirm that wedging indeed causes dramatic increase in planet bearing forces. We are analyzing the mechanisms behind this and the most important design quantities.

- **Idler Gear Dynamics: Analysis and Experiments** – Planetary gears are among the most complex multi-mesh gear system. To develop understanding of how multiple tooth meshes interact in a simpler system, we are conducting analytical, computational, and experimental dynamic studies of an idler gear system (Figure 9). The excellent analytical and finite element agreement is apparent in Figure 10. Our mathematical analysis exposes how the two meshes interact in important ways. One can take advantage of this to "cancel" the dynamic forces at the individual meshes. This project also developed an idler gear test stand to allow research grade experiments. No comparable data exists, and this is a major barrier to validation of existing models. Such validation is critical given the complexity of gear dynamics in multi-mesh systems. Figure 9 shows the developed system. Great care was taken to design for high bearing stiffness, precision of all components to eliminate unmodeled excitations, and high-fidelity measurement systems. While the graduate student carrying out this research is supported by a related General Motors grant, his work is closely aligned with the objectives of the ARO research.

- **Planetary Gear Dynamics Experiments** – With ARO DURIP funding, we built a truly unique experimental gear dynamics test stand (Figure 11a). Figure 11b shows the fixtures for experiments with Boeing using the test stand. This year we completed the first major rotorcraft gear research experiments. The Center for Rotorcraft Innovation is sponsoring the experiments, which have generated exceptional interest among the helicopter contractors. The facility was developed in cooperation with engineers and managers at each of Bell, Sikorsky, Boeing-Philadelphia, Boeing-Mesa, Kaman Aerospace, and ARL/NASA Glenn. No similar facility exists at any academic or industry lab. Using funds from an ARO DURIP grant, we completed the design and manufacture of specialized test fixtures for dynamic experiments on Bell OH58 gears (Figure 12). Data collected so far captures the motions of all the components of a planetary gear in a way that has never been done before. We have completed the design of custom gears for long-term dynamic experiments.

- **Mesh Phasing** – The multiple tooth meshes of a planetary gear are not all at the same mesh condition at a given instant (note that a mesh goes through alternating single and double tooth contact regions in one tooth mesh cycle). Rather, they are all out of phase, in general. This has significant impact on dynamic behavior, load sharing, bearing loads, and maximum tooth loads. One can relatively easily take advantage of mesh phasing to markedly reduce the vibration of selected vibration modes. This was recently proven in work on a wind turbine planetary gear. Figure 13 shows the complete annihilation of a problem resonant response due to mesh phasing implemented from our analysis (note the benefits of improved tooth profile modifications apparent in the same figure). The noise problem, which had stopped the turbine operation and ceased further production by the company, was completely eliminated. Despite their practical importance, mesh phasing ideas have not been adopted by the rotorcraft industry. The PI is lobbying helicopter companies to include mesh phasing in future design upgrades. While mesh phasing is a

fundamental input to analytical models in current industry and research use, it has been erroneously represented in many published works and ignored in others. We previously derived a complete analytical description, validated with computational results, that clarifies this issue. We extended this analysis to the more complicated case of general compound planetary gears (Figure 7).

Main Points

- Planetary gear vibration is inherently nonlinear system due to the contact loss at meshing teeth. This is consistent with experimentally validated findings from single gear pairs where researchers now universally accept the important role of contact loss in dynamic analysis.
- The finite element/contact mechanics/multibody dynamics software we have adopted in parallel with the analytical modeling captures gear response with greater accuracy than any other computational tool, including the major finite element codes. This has been demonstrated by comparisons with benchmark experiments for single mesh gear pairs and a planetary system.
- Tooth profile modifications are one of the most effective noise reduction tools available, as confirmed in single gear pair systems. There is no existing literature on how to introduce modifications in planetary gears, but our research shows dramatic noise reductions are possible with this inexpensive and easily implemented technique.
- There is a glaring need for research grade experiments on the dynamics of multi-mesh systems, and we are developing the only facility in any government, industry, or university lab capable of such experiments. Planetary gears in particular demand such data given the complexity of their dynamics limits confidence in analytical predictions without validation.

V. Technology Transfer

- Presented thorough review of planetary gear vibration program to an Army VLRCOE Review Panel (approx. 20 members from ARL and industry) at Penn State (2008)
- Completed major project with Sikorsky using analytical models from ARO sponsorship to evaluate noise potential of a new CH53K transmission design. In addition to close technical cooperation with several engineers at Sikorsky, the gear dynamics software tool developed at OSU has been transferred to Sikorsky for ongoing use.
- Initiated new project with Sikorsky to adapt an advanced finite element tool for dynamic analysis of gear transmissions, where only static analysis is currently possible.
- Partnering with Penn State on Army Vertical Lift Research Center of Excellence research. The work complements the ARO research.
- Presented research seminar at ARL/NASA Glenn Research Center. (June 2007)
- Gave presentations to high-level helicopter industry and government research staff on planetary gear research progress at Center for Rotorcraft Innovation (CRI) meetings. (February 2007 and 2008)
- Held numerous teleconferences and had continuous design discussions with engineers from Bell, Boeing, Sikorsky, ARL NASA Glenn, and ARL Ft. Eustis on experimental research plans using my ARO DURIP funded planetary gear test stand.
- Participated in formal Drive Systems group meeting at the NRTC/CRI annual review (Feb 2008) to discuss helicopter powertrain research directions. Participants were from all the helicopter companies and several ARL labs.

- Conducting experiments on a Bell Helicopter OH58D gearset using a unique ARO DURIP funded experimental facility.
- Conducted joint experiments with Boeing Helicopter (Philadelphia) using my planetary test stand (developed with ARO DURIP funds) to prove the design advances in Boeing's new double helical planetary design.
- In cooperation with Boeing Helicopter (Philadelphia), we used OSU models to study planetary gear crack vibration signature on a Chinook in parallel with their measured data. These interactions expose rotorcraft contractors to the research tools we have created.
- Continued twice yearly presentations at the Ohio State University Gear Sponsor's Meeting. This meeting is attended by ARL staff at NASA Glenn, Army helicopter contractors (especially Sikorsky and Bell), and over 30 companies active in gear analysis and design.
- Collaborating with Ford on sponsored research for planetary gear experiments using high precision, custom designed gears and test fixtures. Cooperated closely with Ford engineers on the design and manufacture of experimental fixtures.
- Solved a major automotive gear noise problem in cooperation with a team of three engineers at Ford. If not solved, this problem would have canceled a major engine program only 7 months before full production. The team was honored with the Ford Chief Engineer Award in 2007.
- Continued sponsored research project with General Motors on multi-mesh gear dynamics. This is complementary to the ARO work. The findings will advance the ARO work significantly.
- Applied analytical models developed with ARO sponsorship to solve a major gear failure problem in a Honeywell aircraft engine (Phoenix).
- Used analytical models from ARO research to analyze six wind turbine geartrains from multiple companies to minimize their noise potential.

Figure 1: a) Figure indicating location of planetary gear in helicopters (planetary gear drives the main rotor), b) Noise spectrum in an Apache helicopter (note peaks at planetary gear mesh frequency and its harmonics).

Planetary Gear

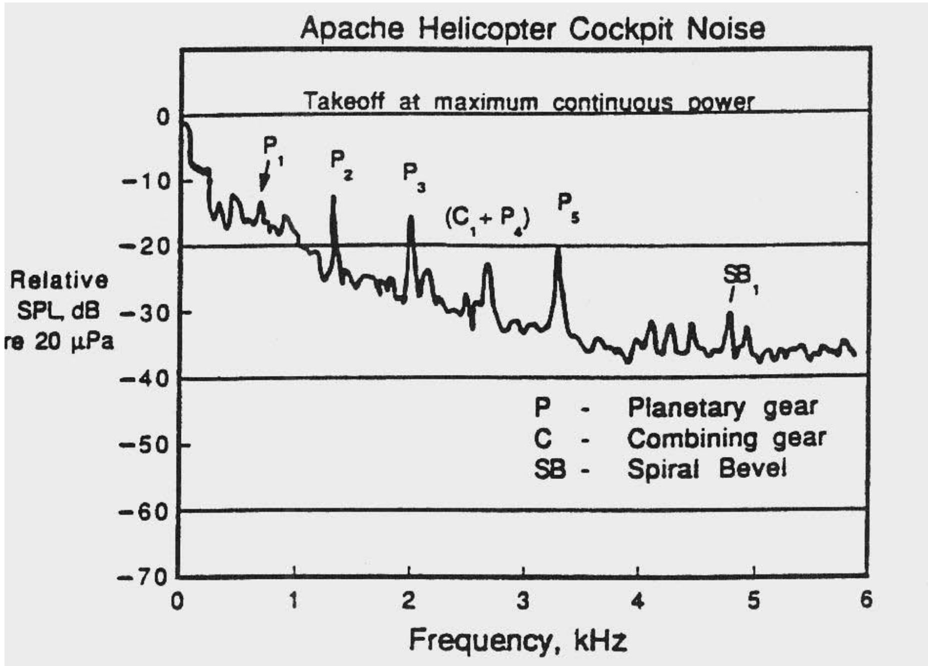


Figure 2: a) Finite element model of a planetary gear (colors denote stresses), b) Analytical model of a planetary gear (springs denote tooth meshes).

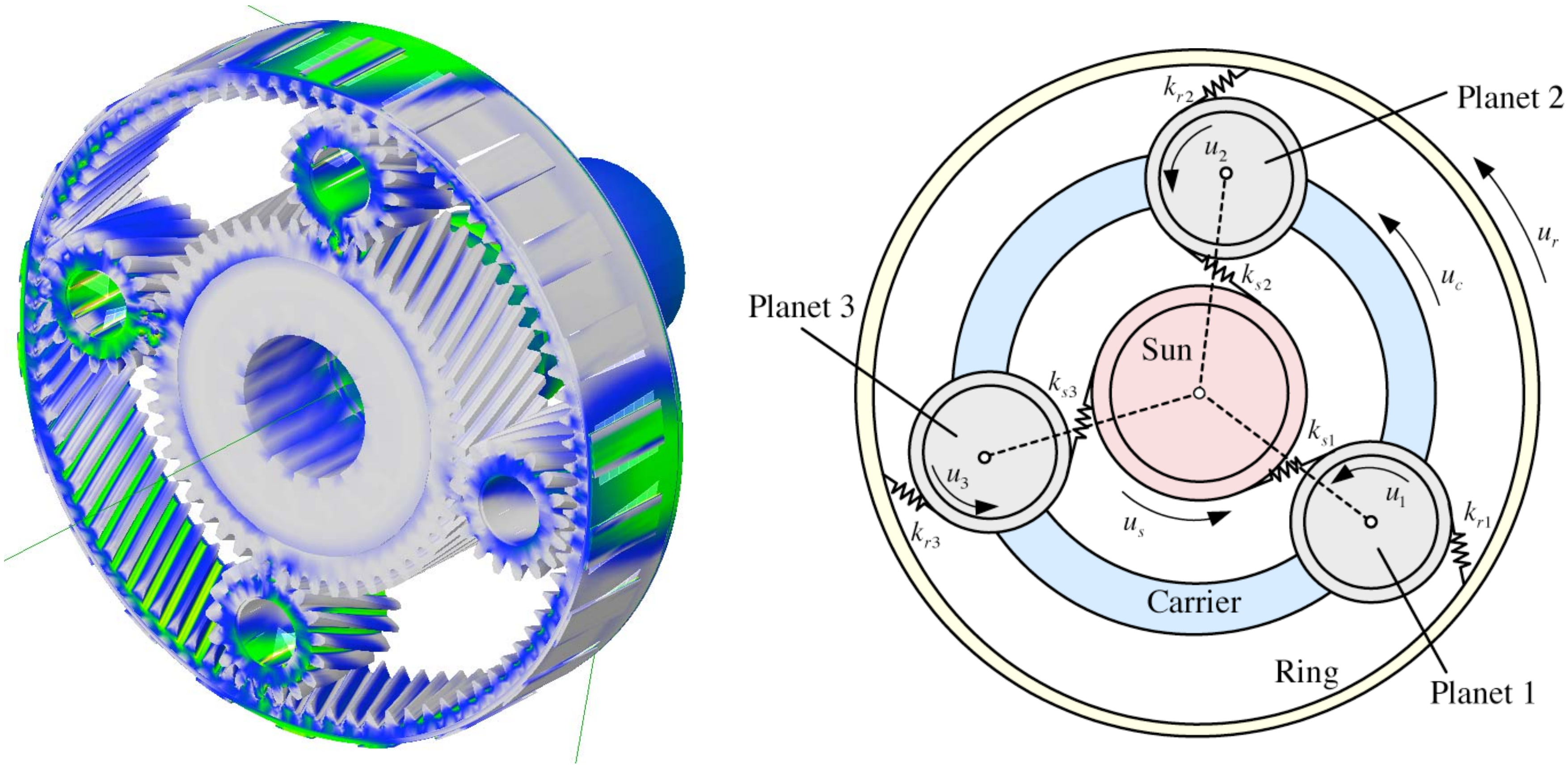
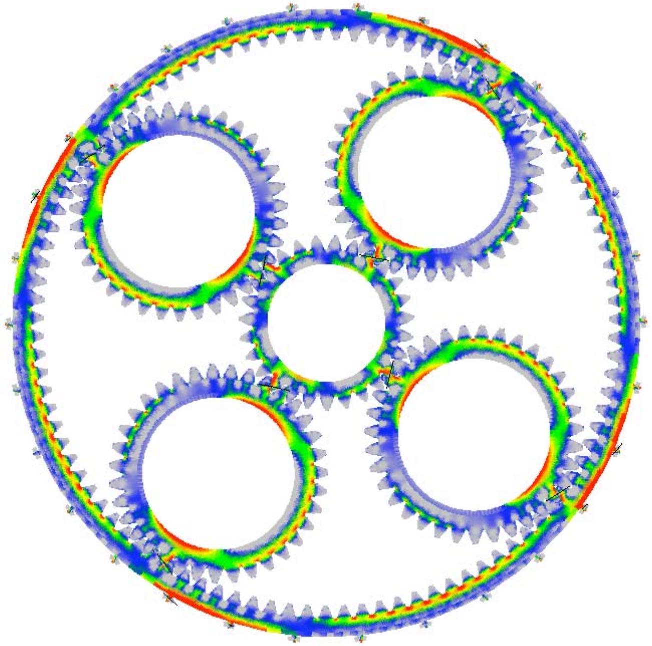
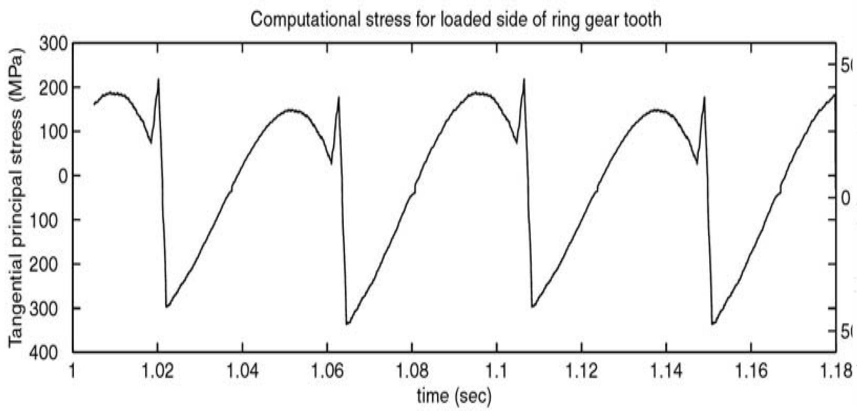


Figure 3: a) Stress distribution (note the ring gear stresses comparable to the contact zone stresses even well away from the planet-ring meshes). b) Comparison of finite element and experimental ring gear tooth stresses for an Army OH58 Kiowa.



Ring Gear Root Stresses: Finite element and Experimental



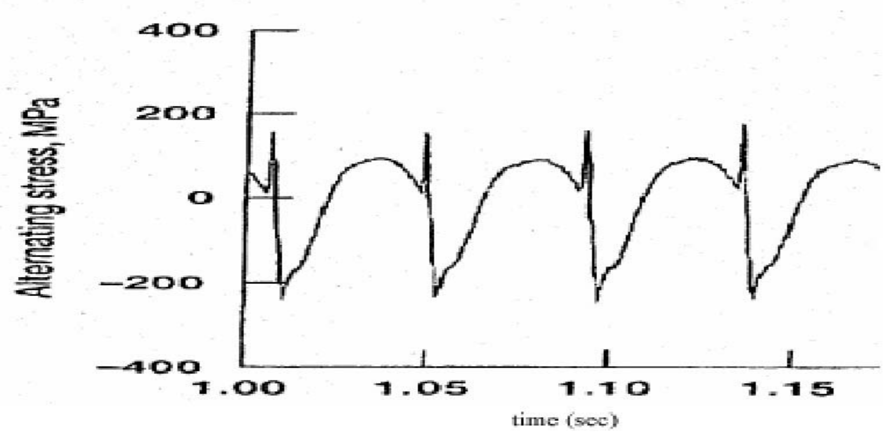
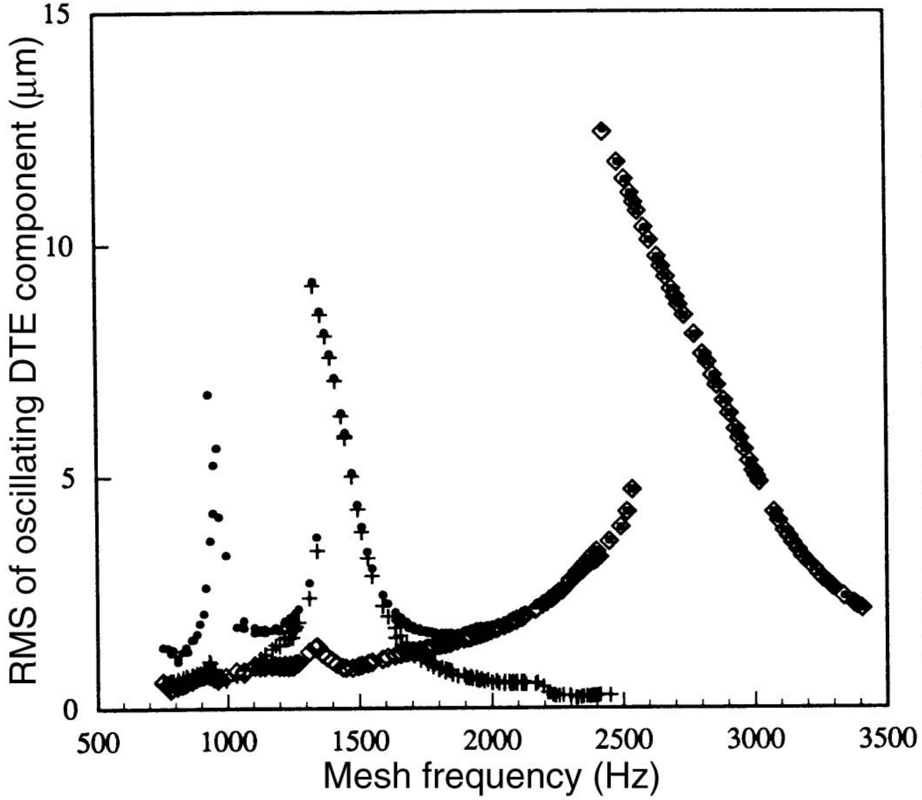


Figure 4: Comparison of experimental and finite element vibration.

Experimental Vibration



Finite Element Vibration

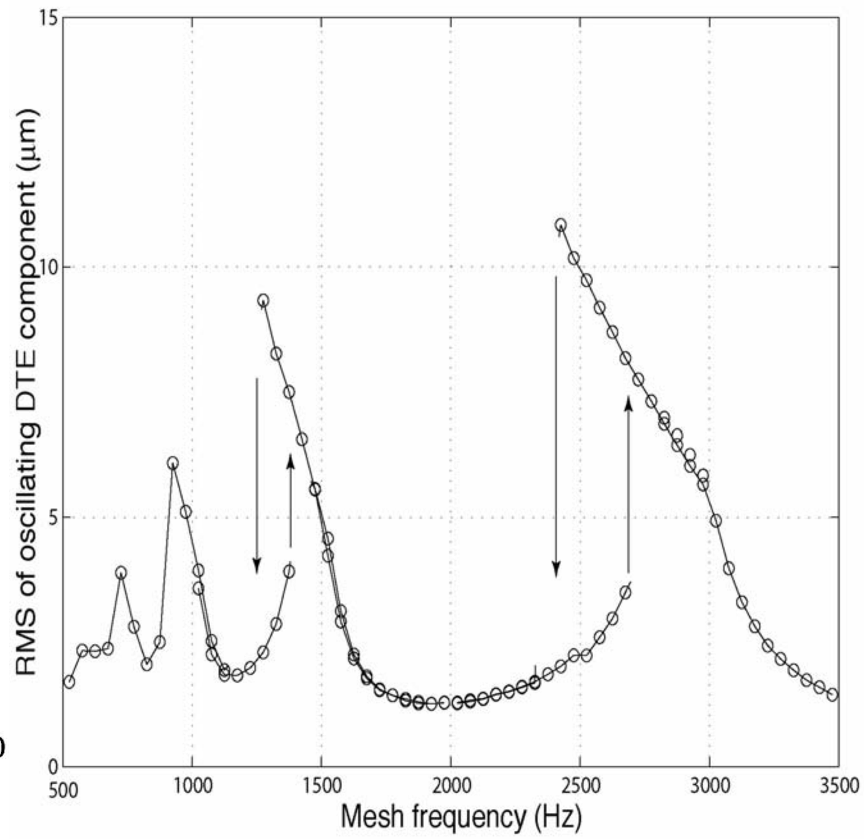


Figure 5: a) Division of Tooth into Inner (analytical) Solution and Outer (finite element) Solution Regimes, b) Mesh of Contacting Teeth (note only coarse mesh required), and c) FE mesh of Army OH58 Kiowa planetary gear.

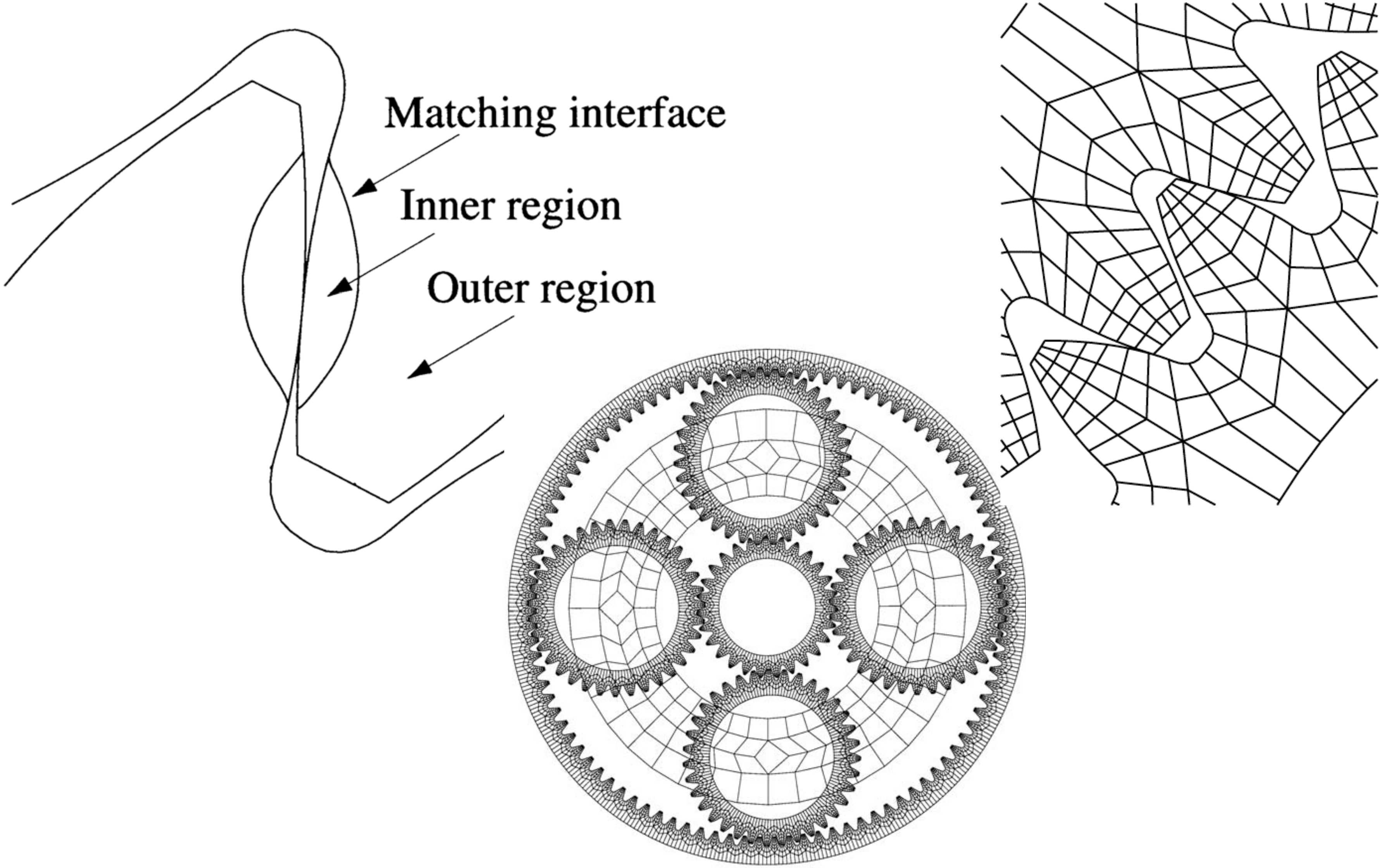
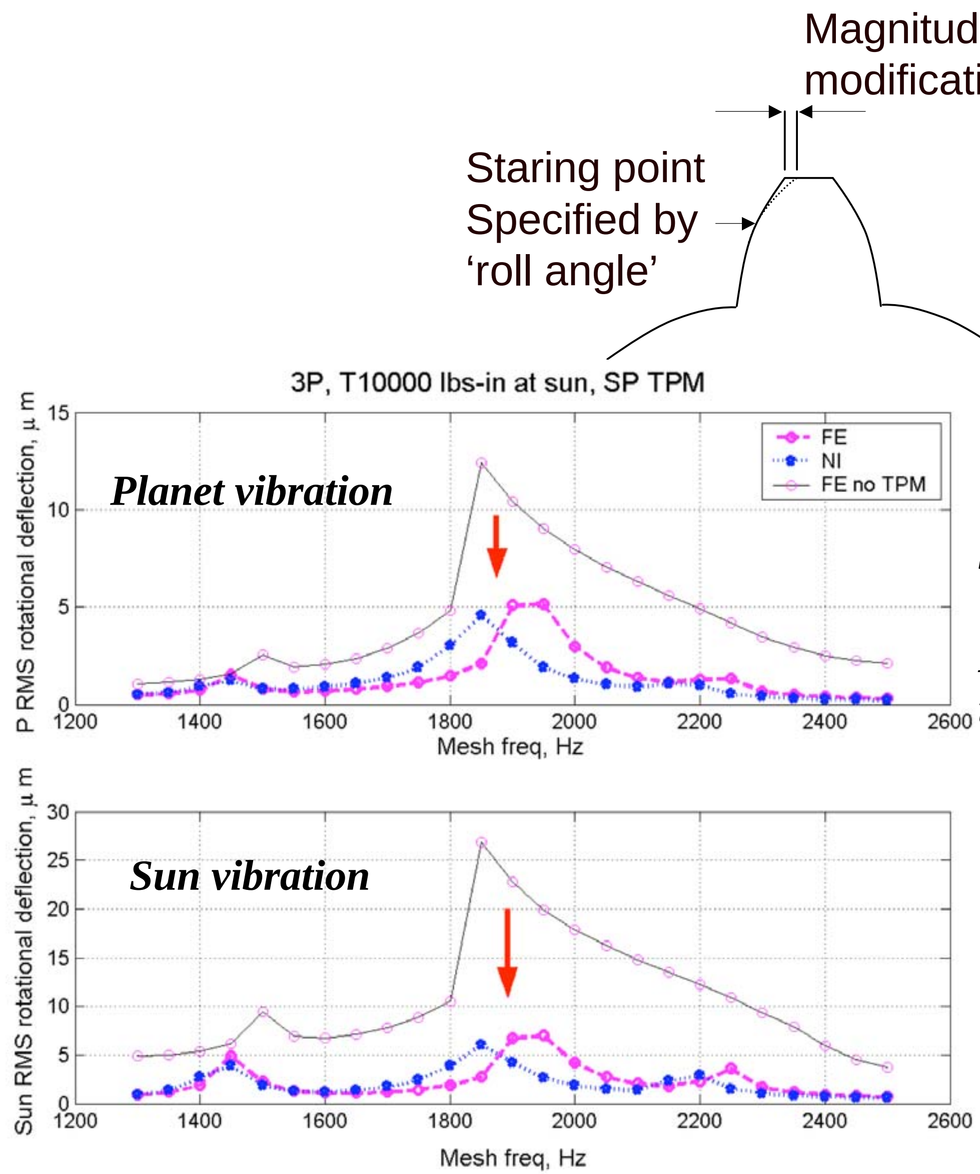


Figure 6: a) Tooth modification uses very slight adjustments of tooth shape to alter vibration, b) Vibration reduction possible with tooth modification.



Solid lines are for unmodified gear teeth

Pink and blue are for modified gear teeth using finite element and analytical models

Figure 7: Types of compound planetary gears: a) Meshed planet system, b) Stepped planet system.

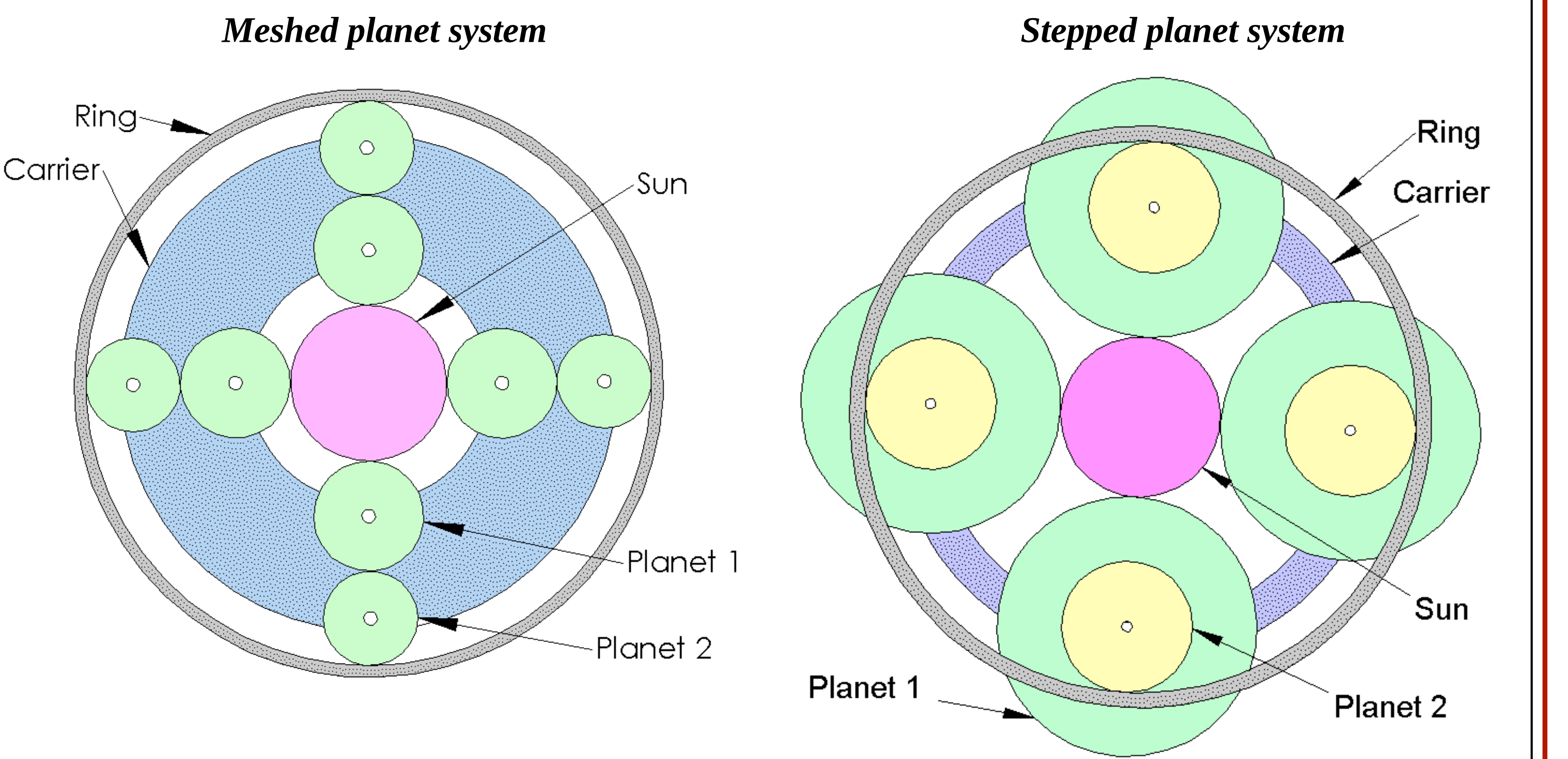
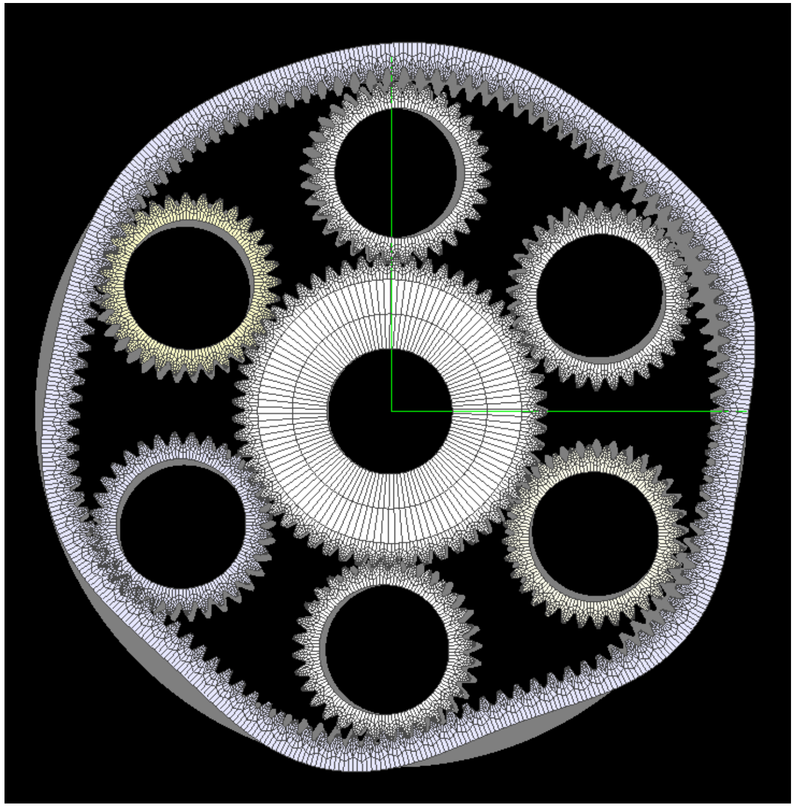


Figure 8: a) Deformed ring gear from finite element analysis (deflection is exaggerated), b) Analytical model that captures elastic vibration of the ring gear.



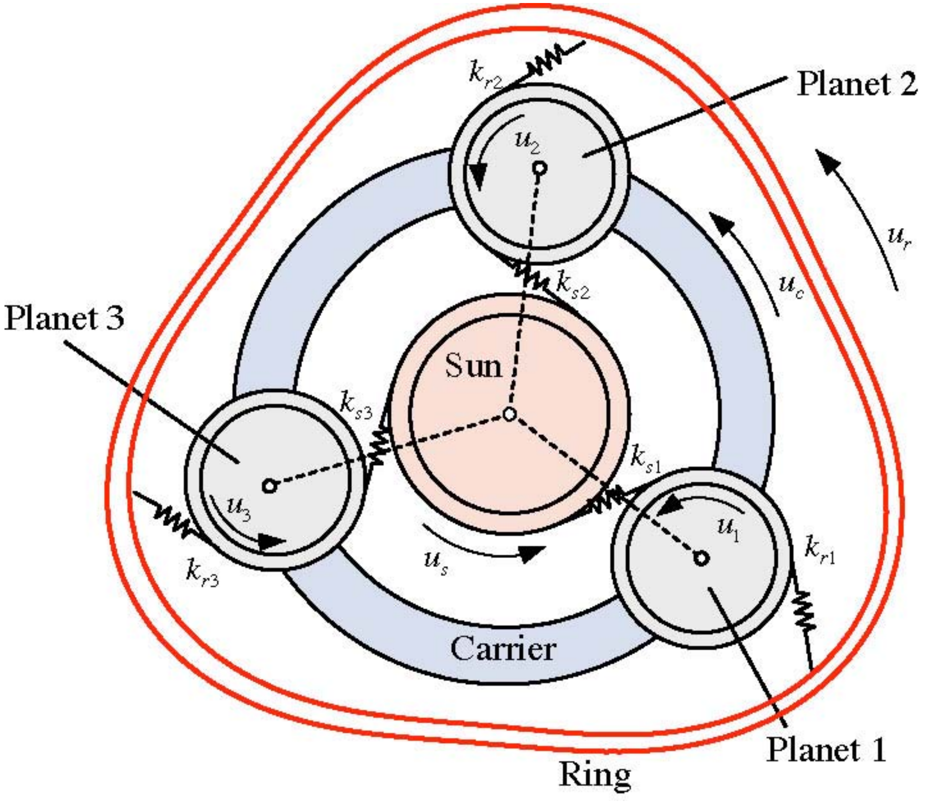
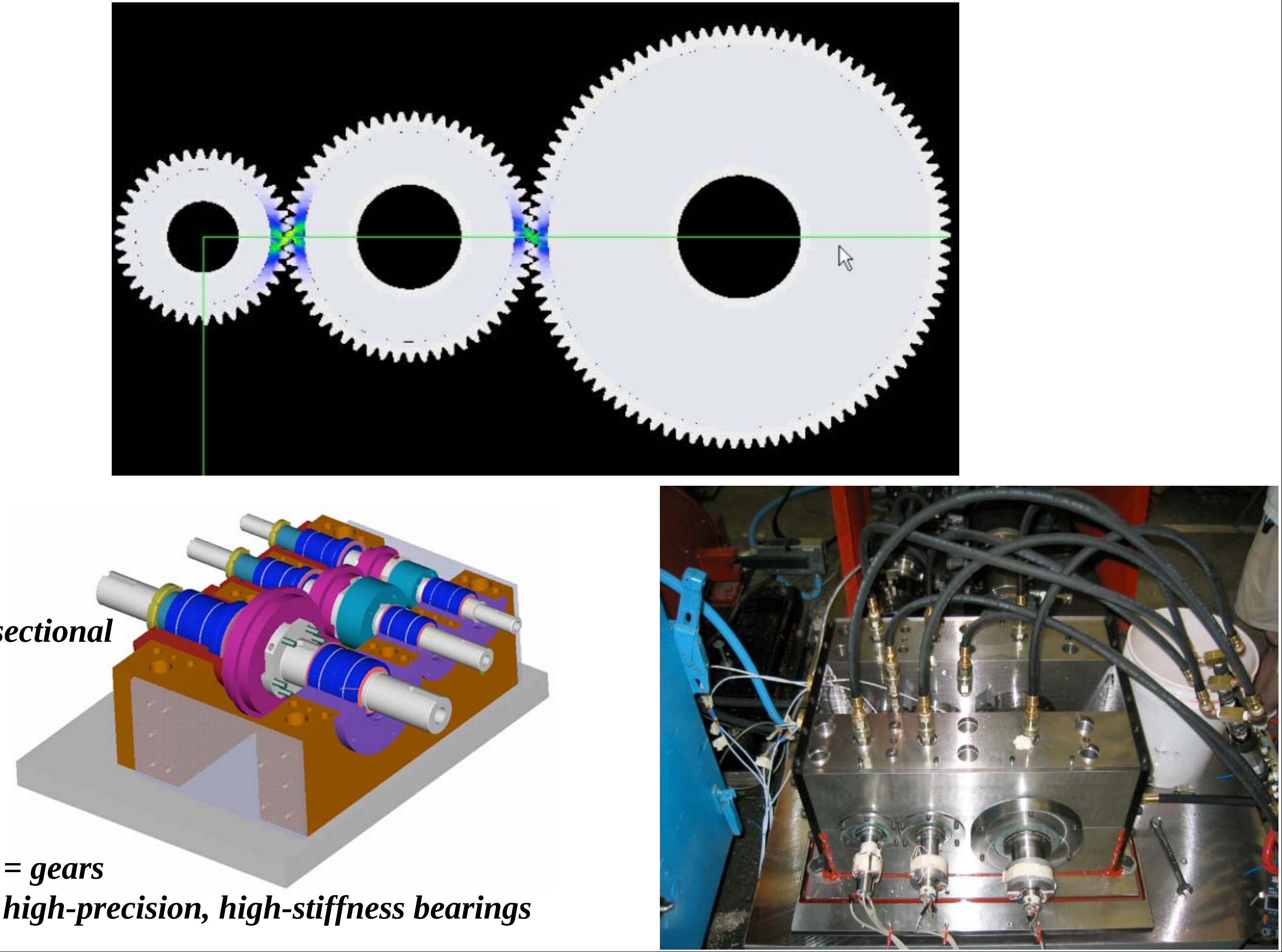


Figure 9: a) Finite element mesh of three gear (idler) system. b,c) Experimental test setup for idler gear dynamics.



Cross-sectional view

Purple = gears
Blue = high-precision, high-stiffness bearings

Figure 10: Idler gear analytical-FE vibration comparison

Vibration as measured by dynamic mesh deflection of one of the idler gear meshes for changing speed. Three torque values are shown.

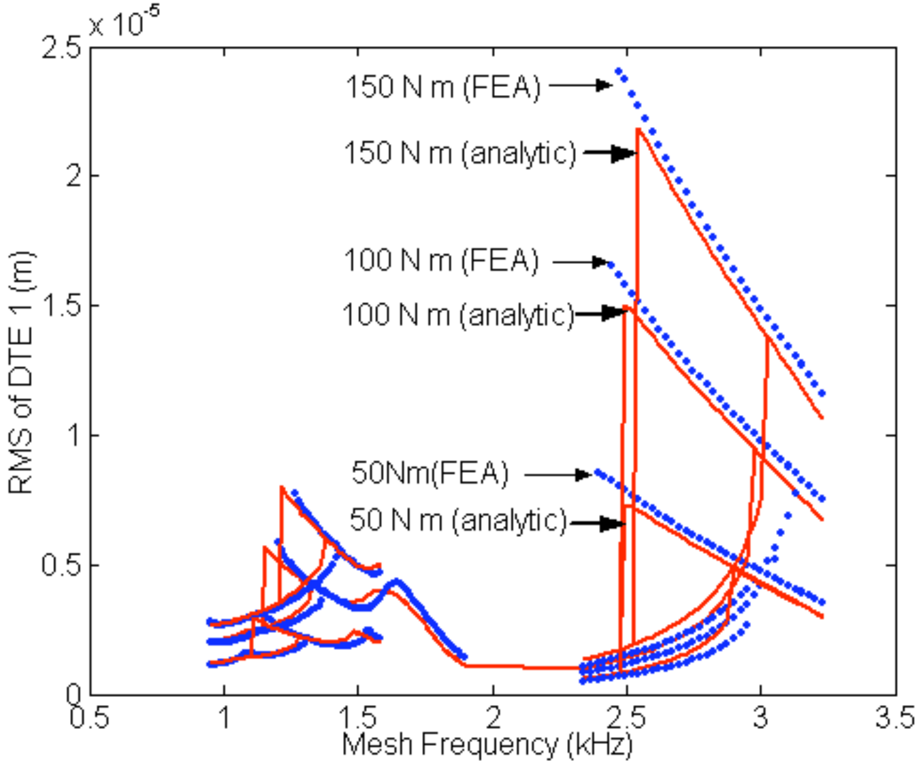


Figure 11: (a) Test stand designed for planetary gear dynamic experiments with the PI's ARO DURIP award. (b) Test setup for experiments on new Boeing helicopter planetary gear design.

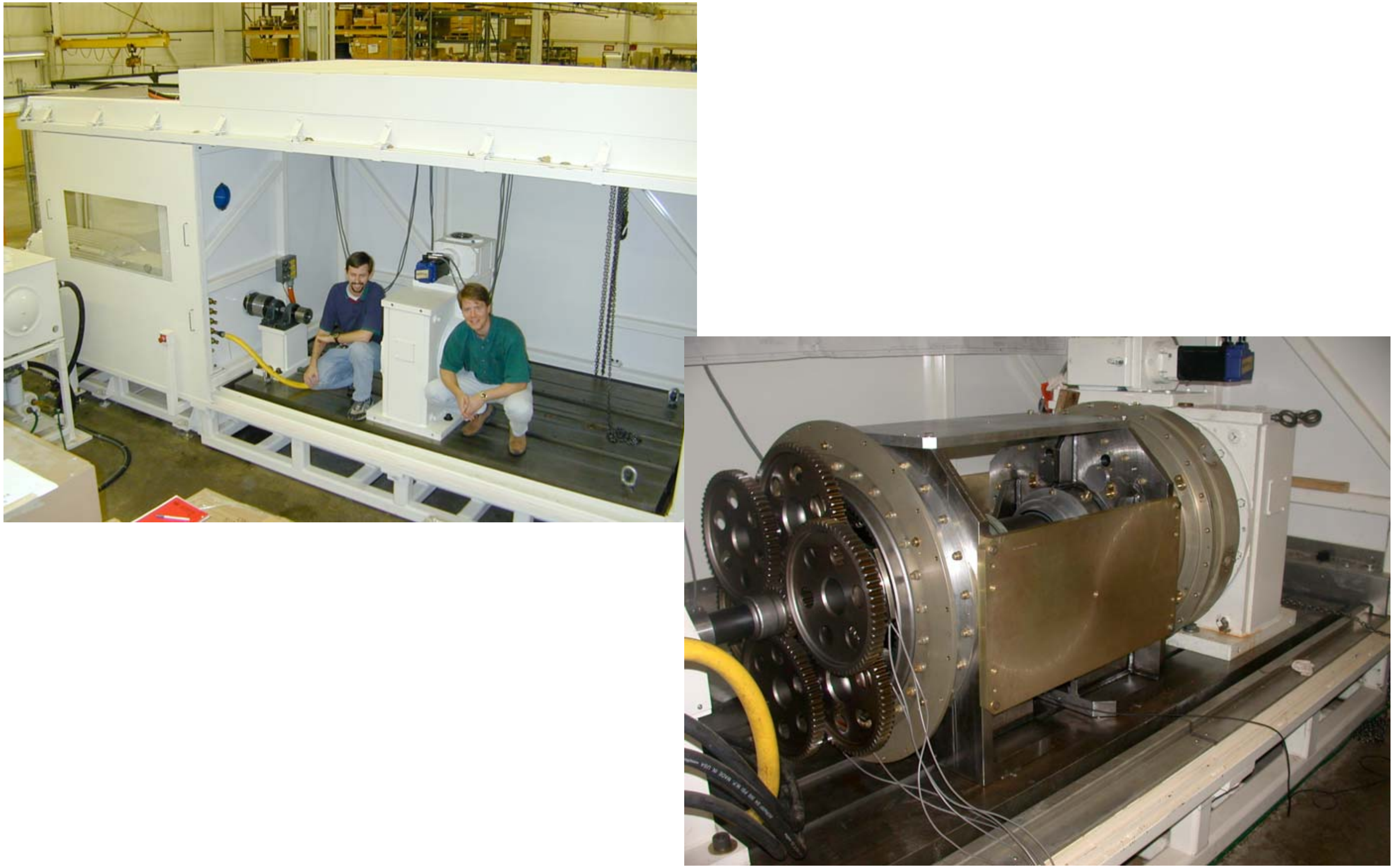
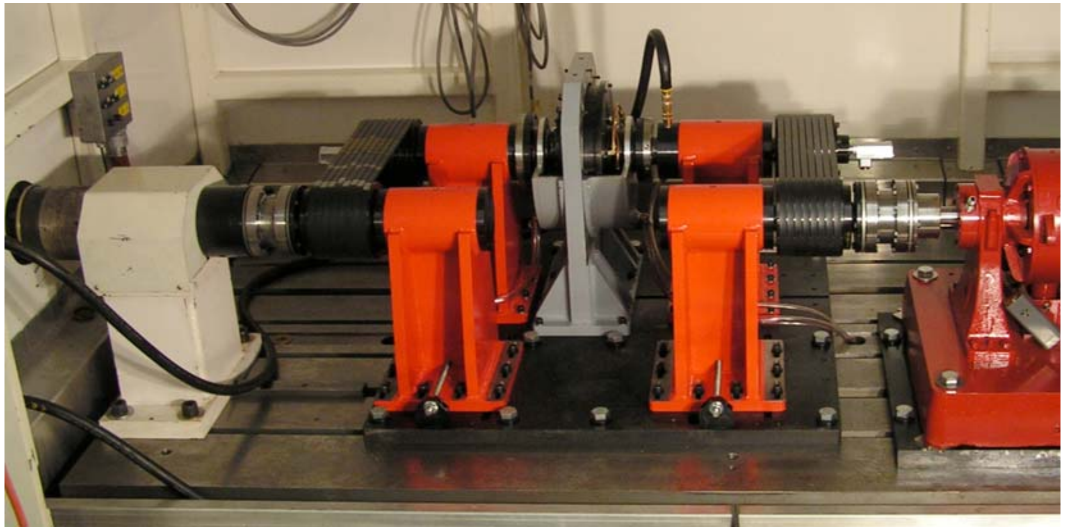


Figure 12: Precision fixtures designed and manufactured for planetary gear dynamic experiments with the PI's ARO DURIP award.



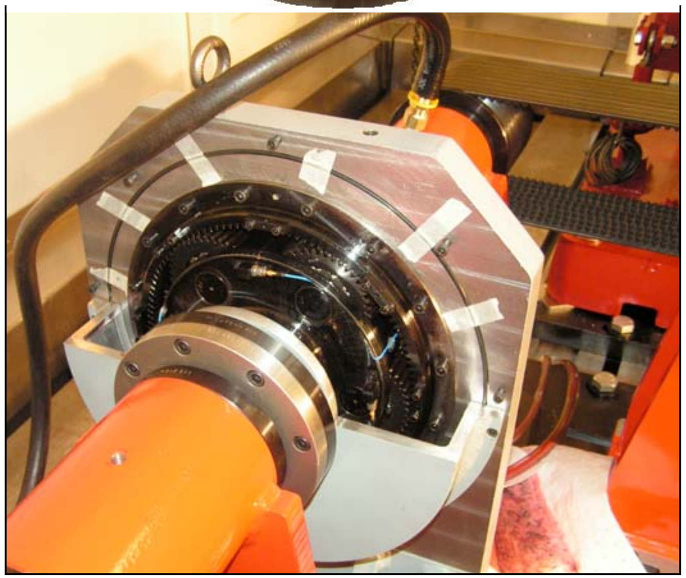


Figure 13: Example of how changed mesh phasing completely eliminated a major resonance in a wind turbine planetary gear. Similar ideas can be applied to rotorcraft gears. Also note the benefits of improved tooth profile modifications (see Fig. 6 and related paragraph in Proj. Summary Sheets) evident in the data.